Delta-doped high purity silicon UV-NIR CCDs with High QE and Low Dark Current

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Infrared and Photoelectronic Imagers and Detector Devices II
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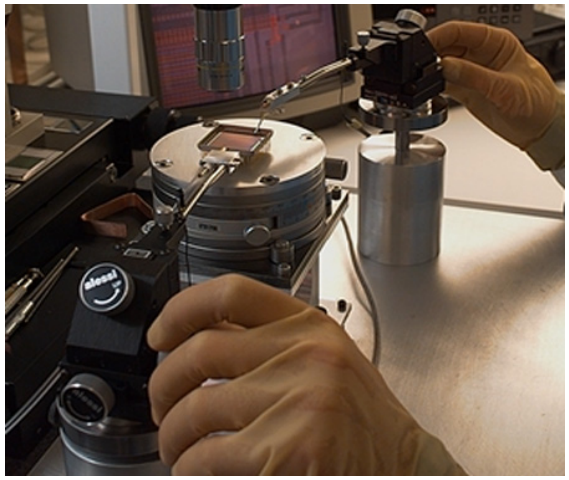
Outline

- JPL Capabilities
- Science Relevance
- P-channel CCDs
- Delta doping technology
- Delta doping p-channel CCDs
- Large format CCDs
- Antireflection coatings
- Summary

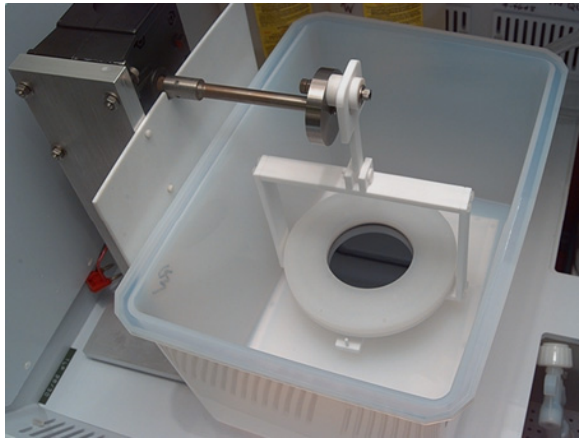
Facilities for End-to-end Post-Fabrication Process



Fully-processed arrays fabricated at outside foundries are obtained.

Bonding

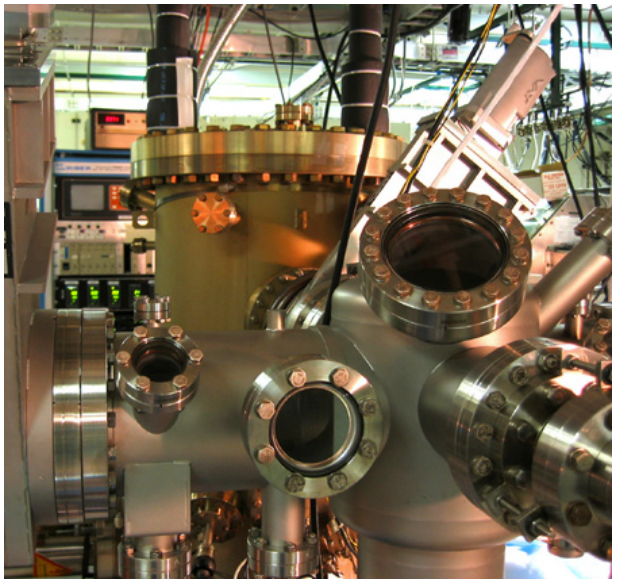
Thermocompression bonding or post MBE bonding is used for achieving flat, robust membranes



Thinning

Excellent quality thinned CMOS and CCDs have been demonstrated.

Delta-doping



MBE is used to grow a delta-doped layer of Si on the backside of fully processed silicon arrays .

Response of CCDs is enhanced to the theoretical limit.

Chemical Mechanical Polishing (CMP)

Deposition of AR Coatings and Filters

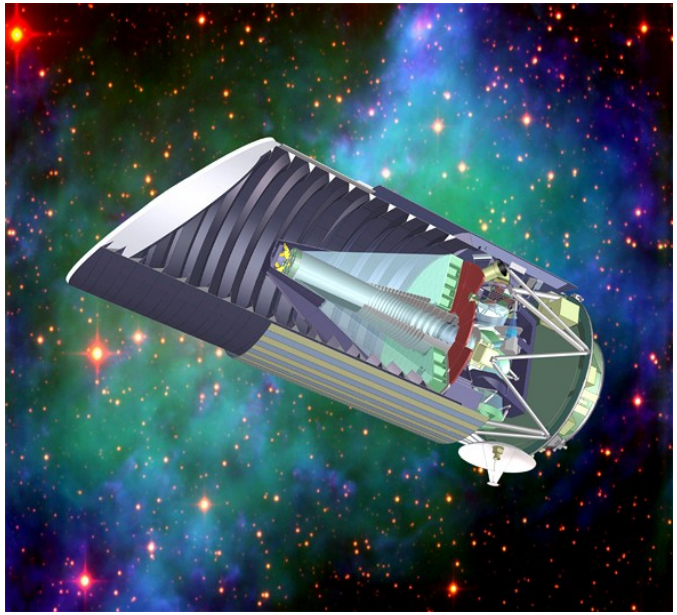
Modeling capability and PECVD and sputtering system for deposition of filters and AR coatings

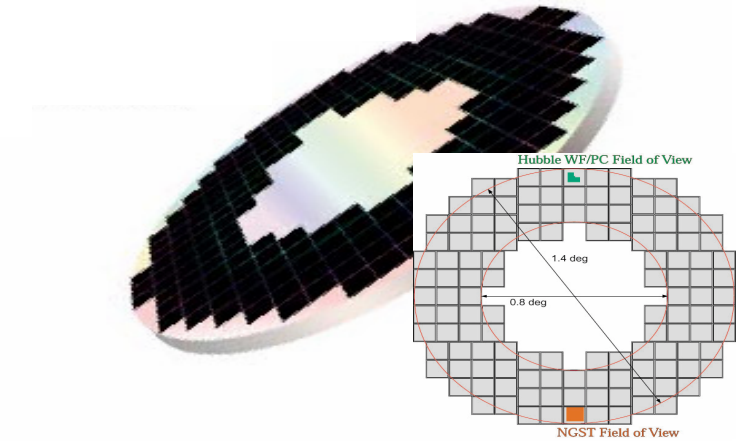
Versatile approach makes it possible to work with various imaging arrays and technologies

Super Nova Acceleration Probe (SNAP)

Fundamental cosmological questions:

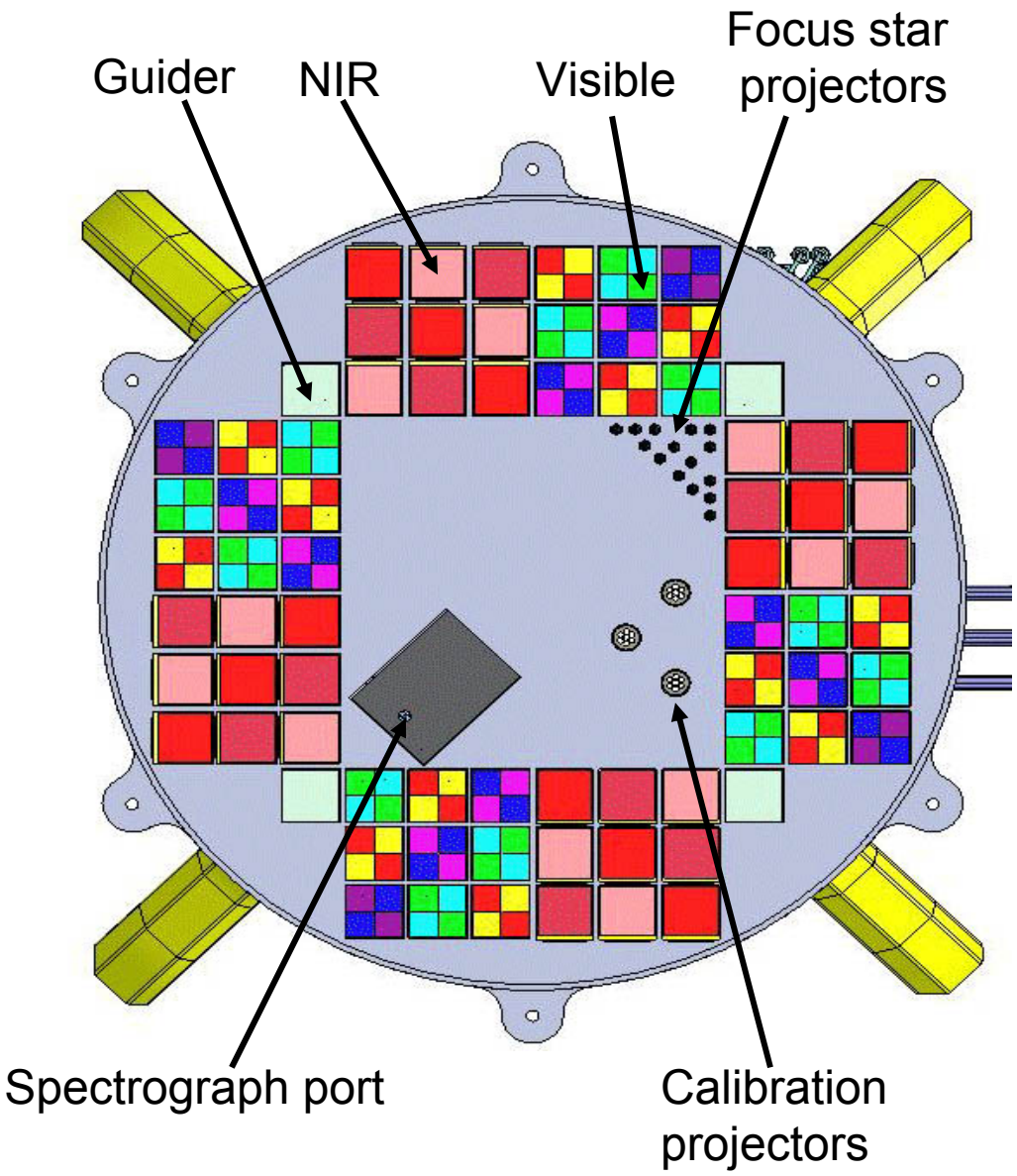
- ***Expansion history of the universe over the last 10 billion years***
- ***Fundamental test of inflation***
- ***What is the nature of dark energy?***

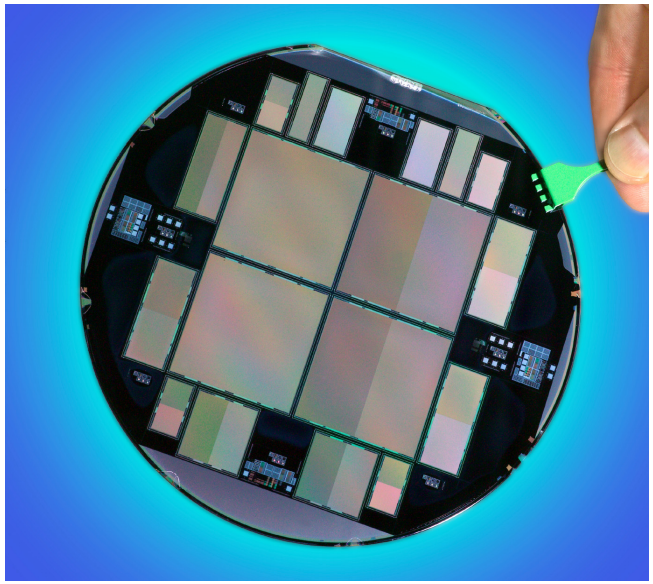




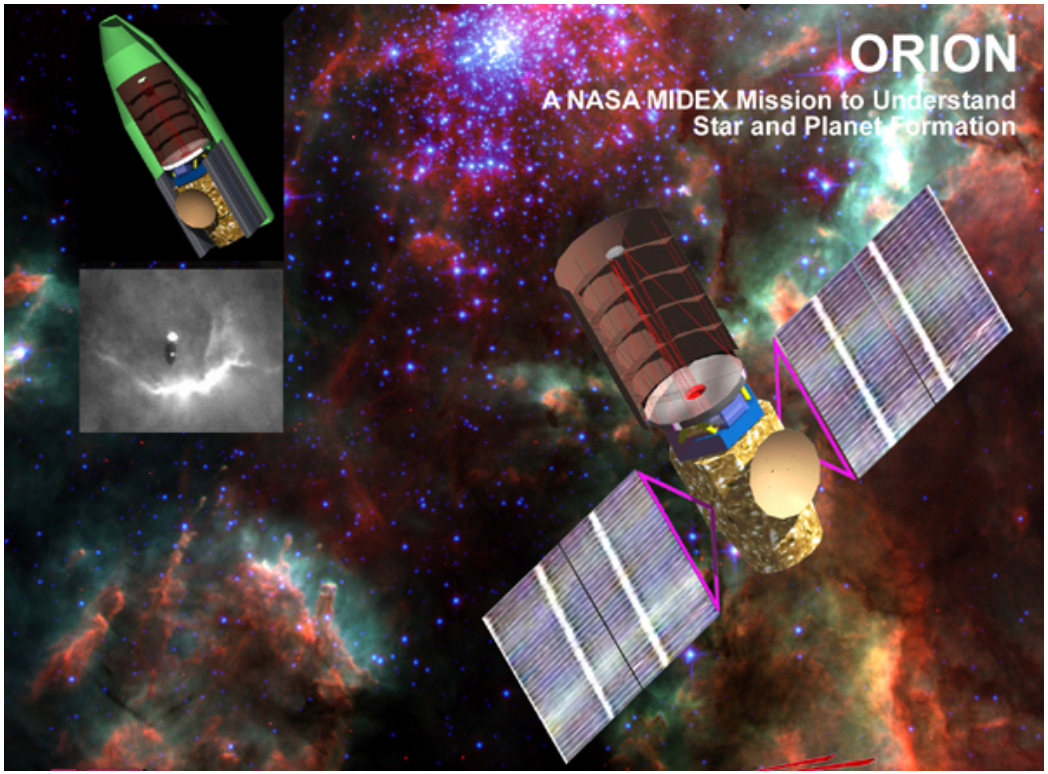
SNAP FPA requirements:

- Spectral Range*:* 350-1000 nm
- Format: 36 CCDs (3.5kx 3.5k) mosaic
- High QE, Low dark current
- High photometric accuracy


Guider
NIR
Visible
Focus star projectors
Spectrograph port
Calibration projectors



MIDEX Orion and Detector Requirements



Science Objectives

High spatial resolution optical surveys of star forming solar neighborhood,

High spatial resolution survey of Magellanic Clouds,

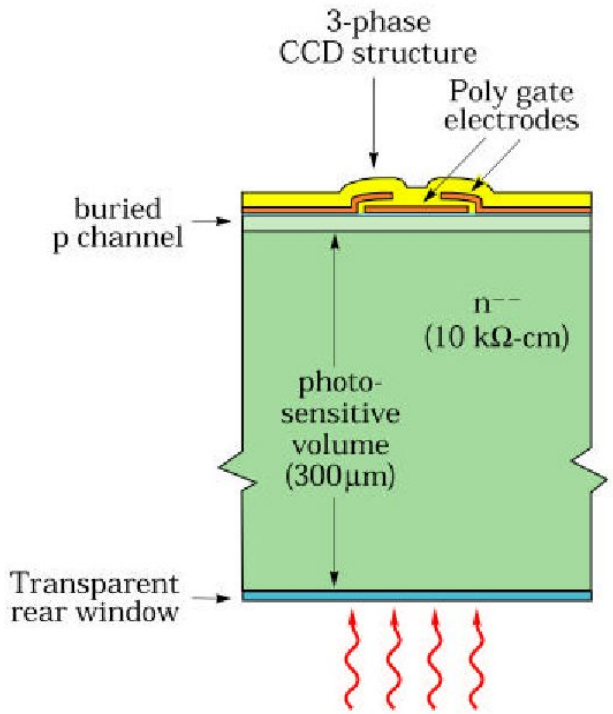
Survey of representative sample of external galaxies

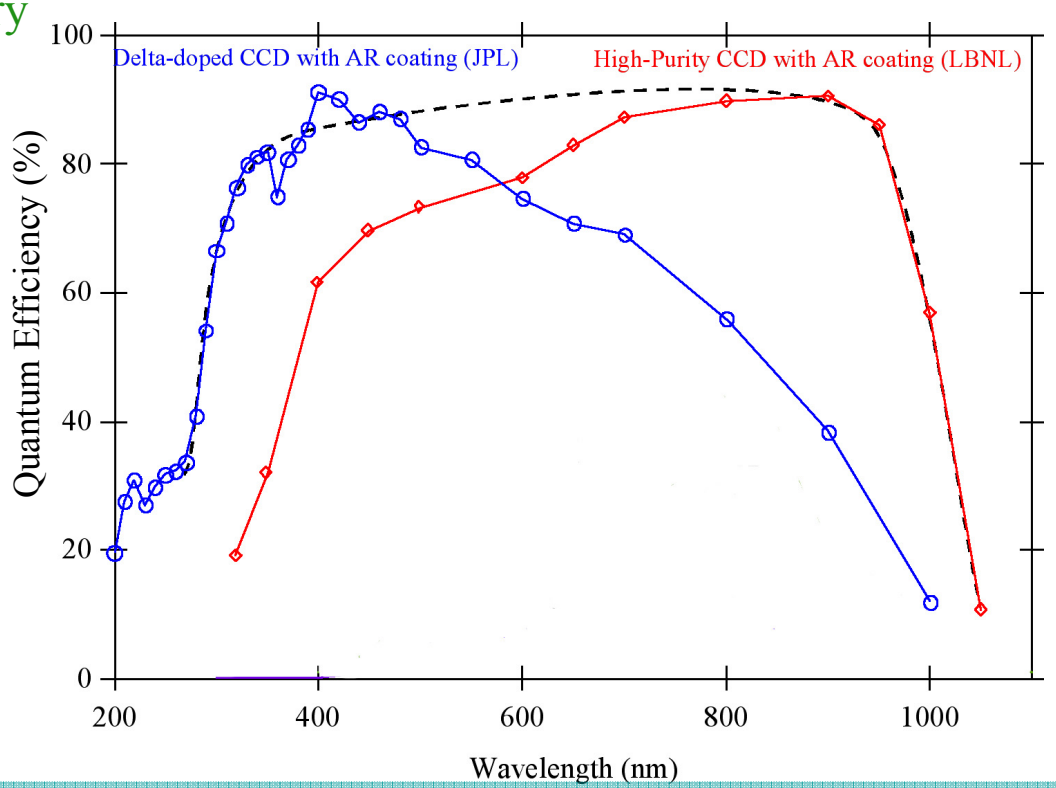
Key Requirements Focal Plane

- Spectral Range: Two channels 200-510 nm and 510-1000 nm
- Format: 8K x 8K CCD (mosaic), Pixel size (15 μm)
- Quantum Efficiency: 80% at 656 nm, 60% at 373 nm, 50% in the UV,> 60% at 900 nm

P-channel High Purity CCDs and Delta doping

High purity silicon imagers
Lawrence Berkeley National Laboratory





Merge Delta doping with High purity Array Technology to achieve high QE& broadband response

Allow streamlined fabrication because of the low temperature process of delta doping

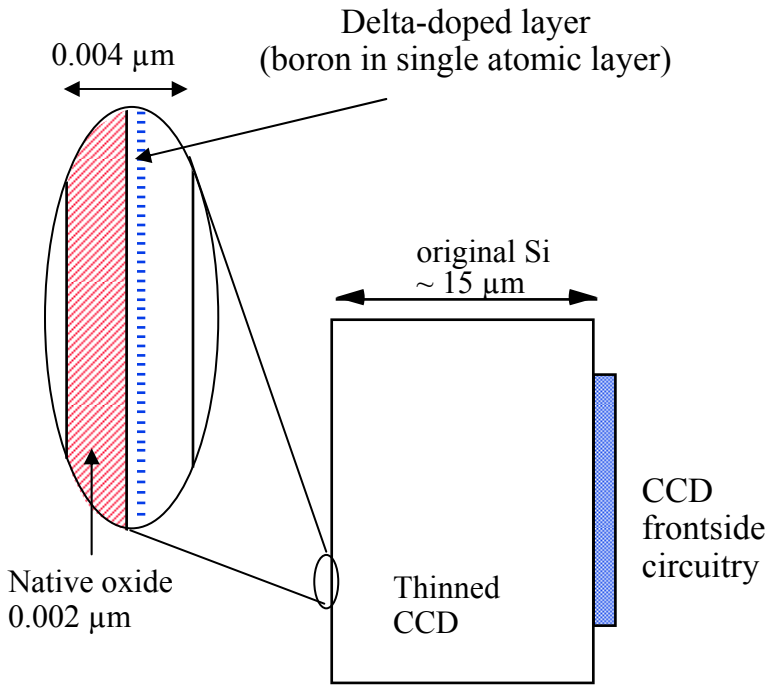
The transparent electrode plays key role in: QE, dark current, spectral range, and fabrication

Molecular beam epitaxy (MBE) has potential advantages in all the key issues

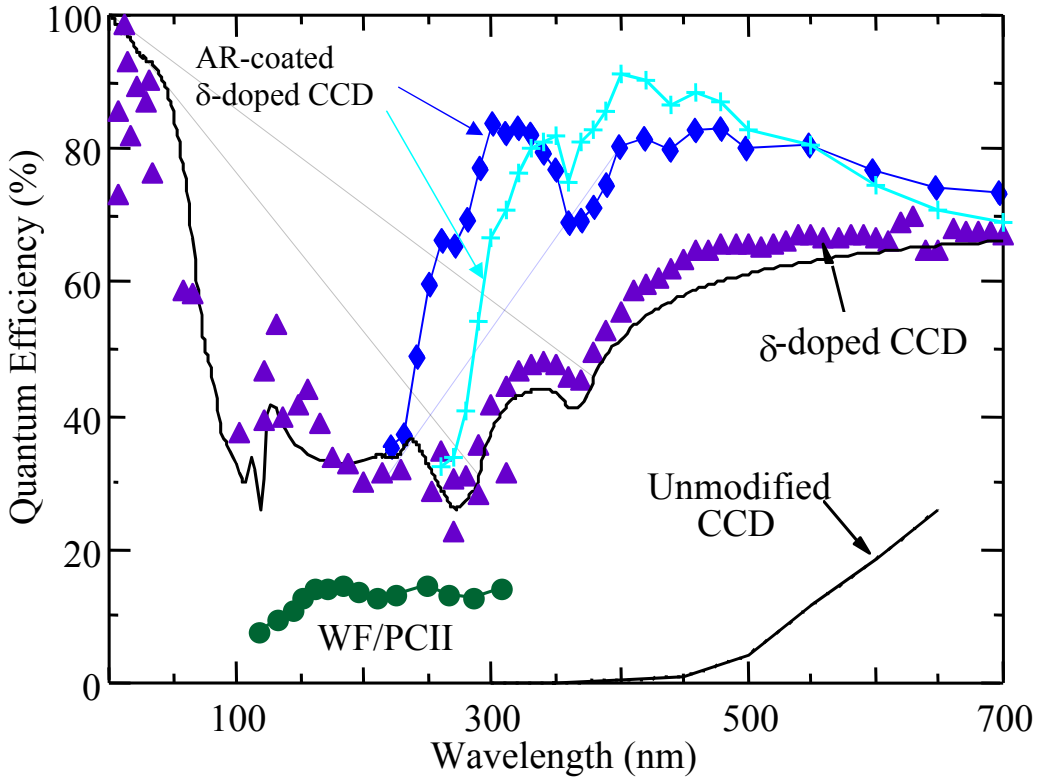
What is Delta doping?

Fully-processed devices are modified using Molecular Beam Epitaxy (MBE)

Cross section delta-doped CCD structure



Hoenk et al., *Applied Physics Letters*, **61**: 1084 (1992)



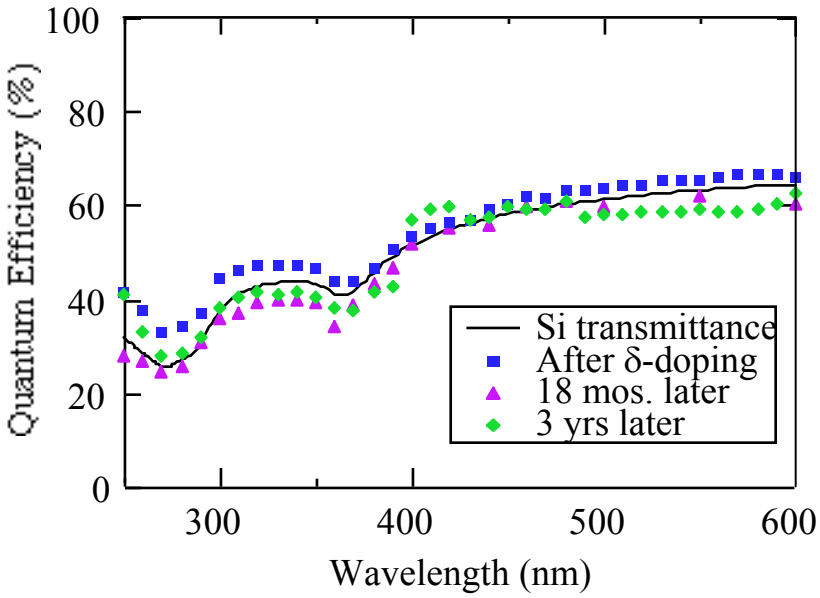
Delta doping provides the maximum possible QE

Key Features

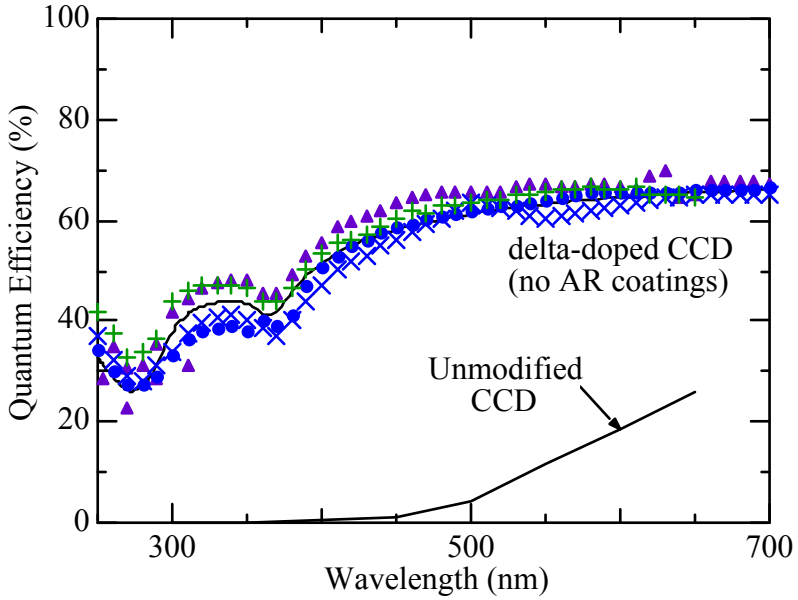
- *Low temp. growth (< 450 C)* Fully-processed devices
- *Ultrathin electrical contact* High and stable sensitivity
- *Surface passivation* Low dark current, full depletion

Long-term Stability, QE Hysteresis, and Reproducibility

QE stability



QE reproducibility:
Delta doped Loral, SITe, and Reticon CCDs



- Delta doping provides the maximum possible QE and stability from visible to EUV
- Demonstrated technology with different formats and CCD manufacturing processes

Book Chapter: "*Delta-doped CCDs*", S. Nikzad, in "Charge-Coupled Devices" by J.R. Janesick, SPIE Press Vol. PM83.

Delta-doping High Purity P-channel CCDs

Advantages

- Delta doping enables high QE and stability across the entire spectral range attainable with silicon
- Delta doping is a low temperature process and is compatible with fully-fabricated detector arrays.
- Same base device for Orion two channels
- High radiation tolerance and no thinning requirements of high purity p-channel CCDs are additional advantages.

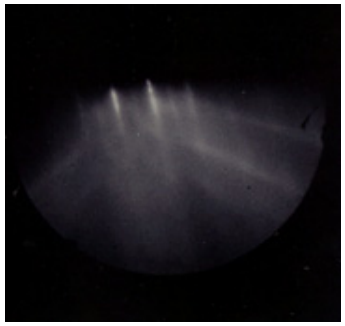
Development

- *MBE techniques and processes had been developed for n-channel devices, i.e., p-type substrates with boron doped delta layers*
- *New epitaxial techniques and surface preparation techniques for delta doping with antimony and handling high purity silicon were developed for p-channel CCDs (n-type delta doping)*

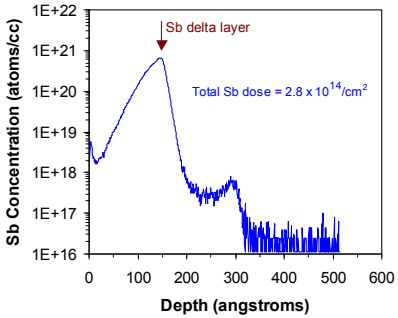
MBE growth on Si substrates and Fully-fabricated Devices

- **Demonstrated an *entirely ultra low temperature MBE process for thin, highly (Sb)-doped epitaxial layers on n-type high purity wafers*.**

Reflection High Energy Diffraction (RHEED)

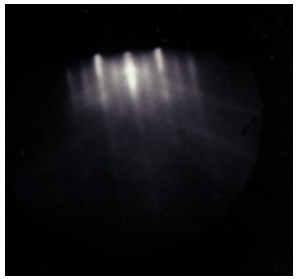


Secondary Ion Mass Spectrometry (SIMS)

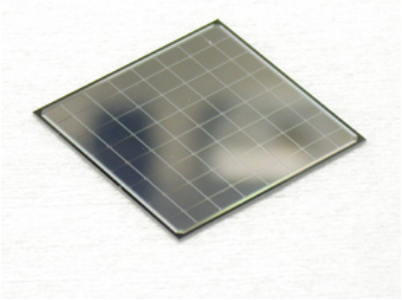


- **Successfully extended the process to PIN diode test arrays, and CCDs…….**

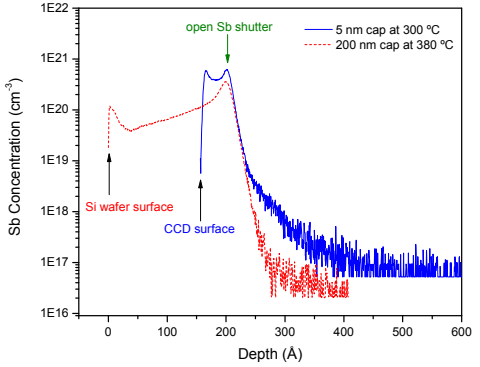
RHEED



PIN Test Array



SIMS



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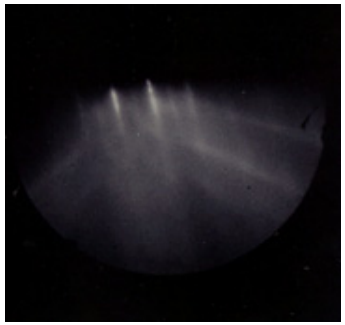

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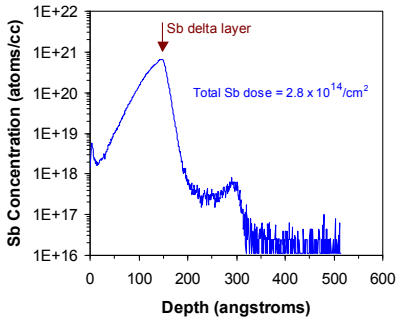

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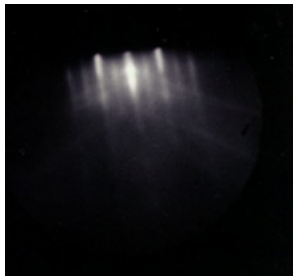
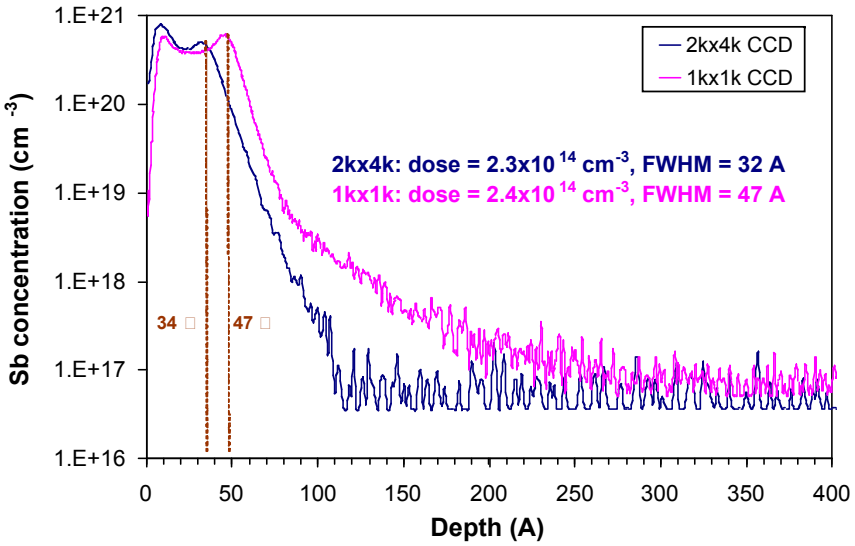
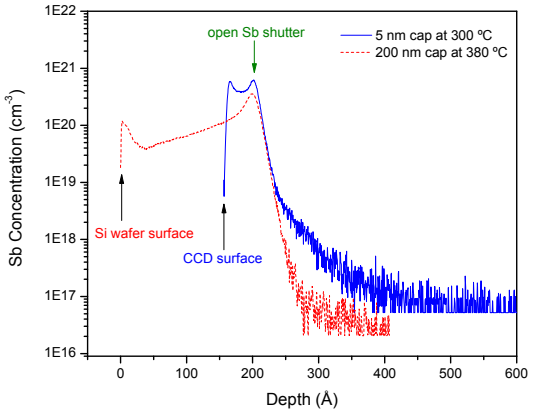
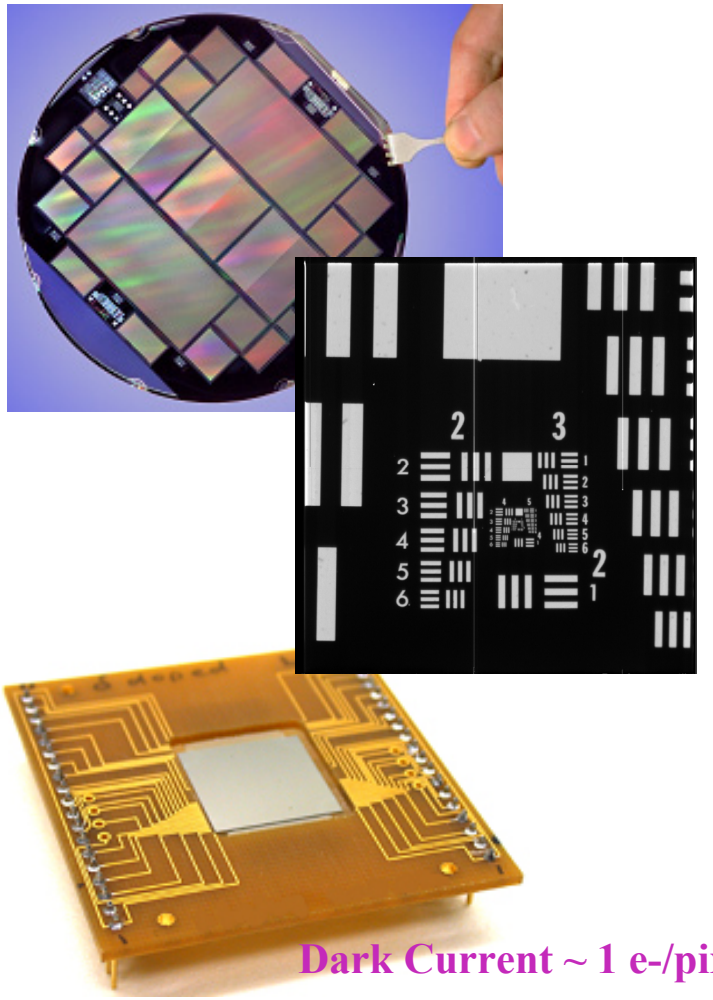
RHEED



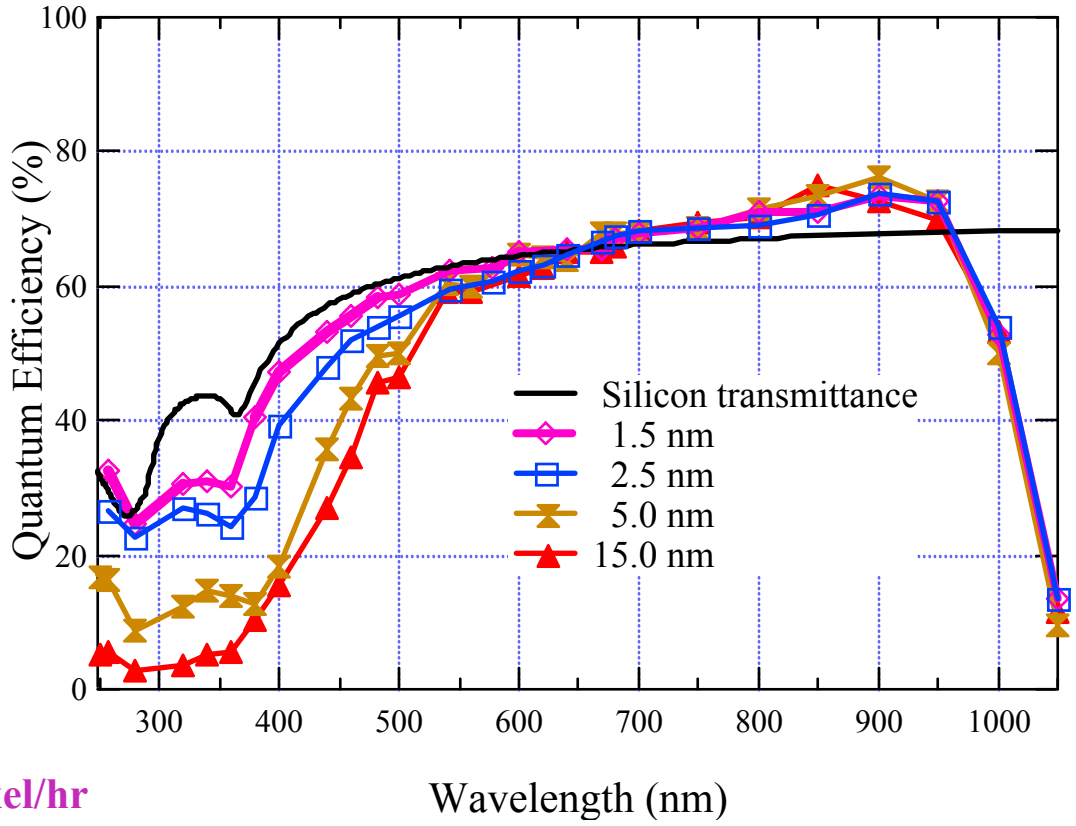




Optimization of Delta layers--Ultrathin layers with high charge concentration



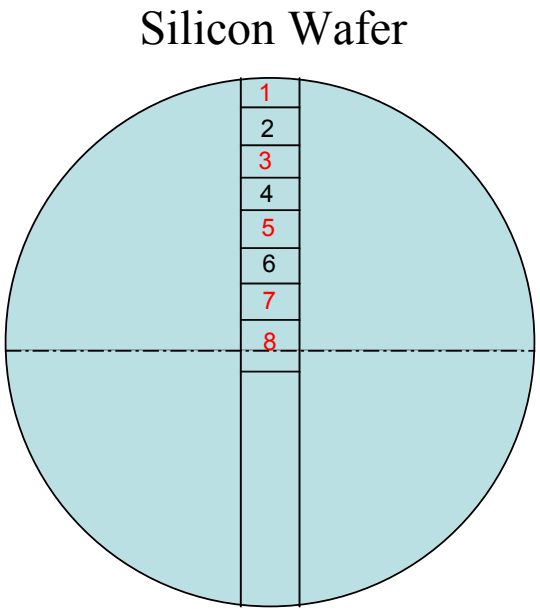
MBE Growth on High Purity CCDs
(No AR coating)

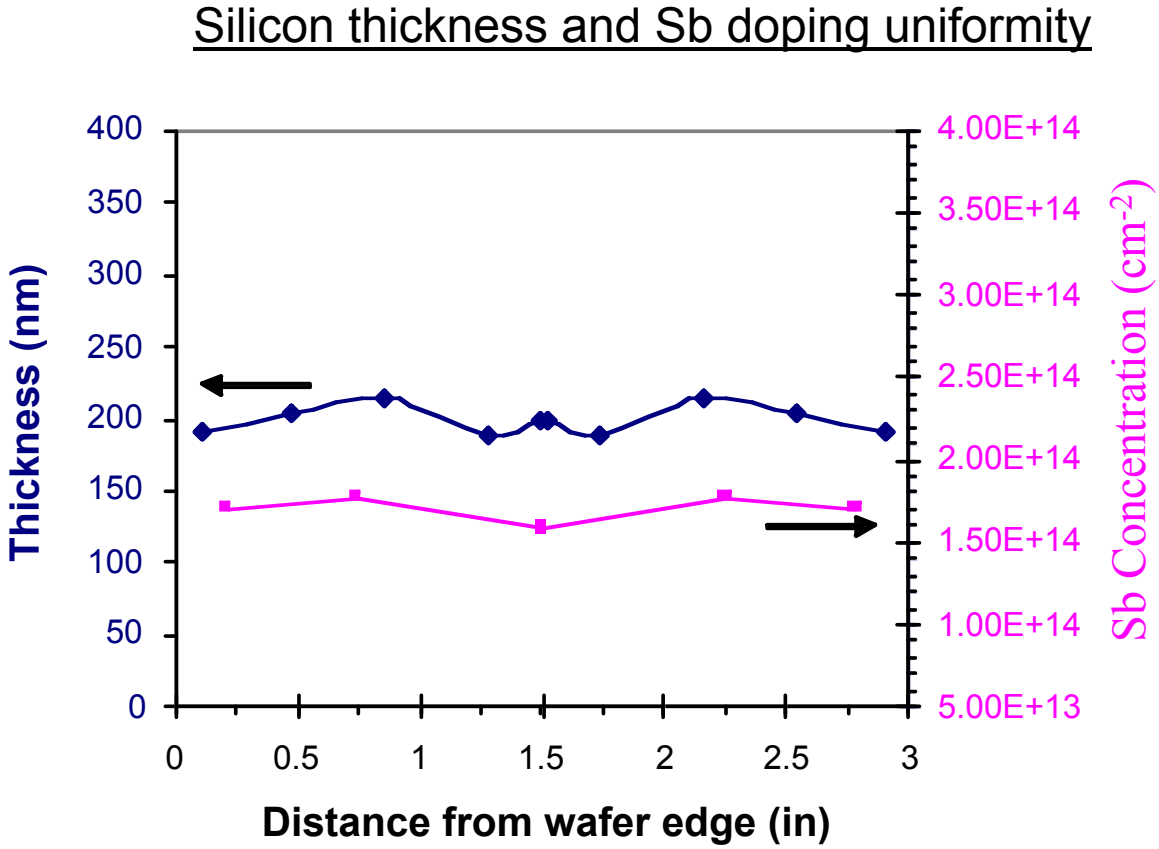


Dark Current ~ 1 e-/pixel/hr

High resolution, high QE, and low dark current demonstrated with MBE-modified high purity CCDs.
Progressively thinner layers on 1K x 1K CCDs show improvement in the blue response
Nearly 100% internal QE with *Thinner MBE layers*

Large Area Uniformity of Delta doping

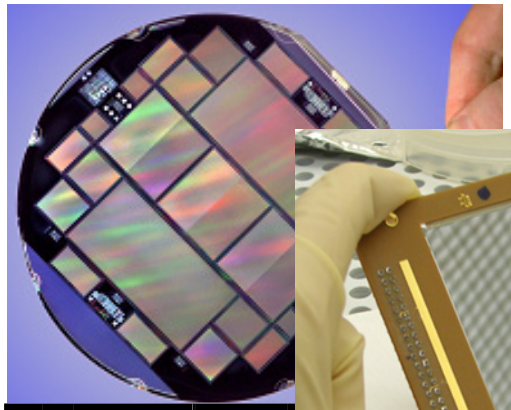


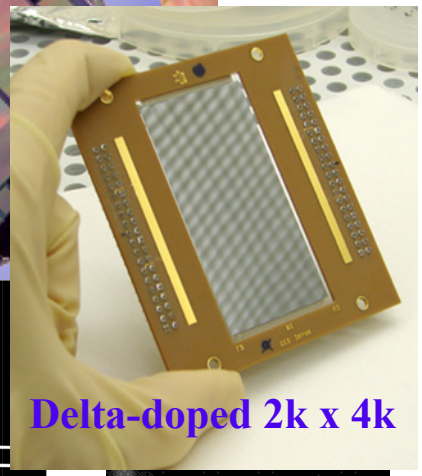


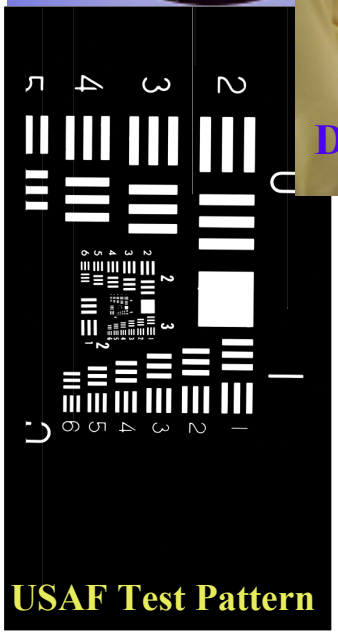
Uniformity of thickness and dopant incorporation was examined across a silicon wafer

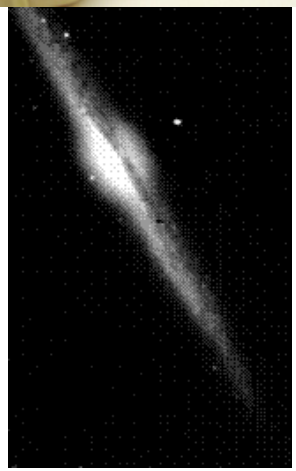
Variation of the order of <10% was achieved.

Delta doped Large-format CCDs

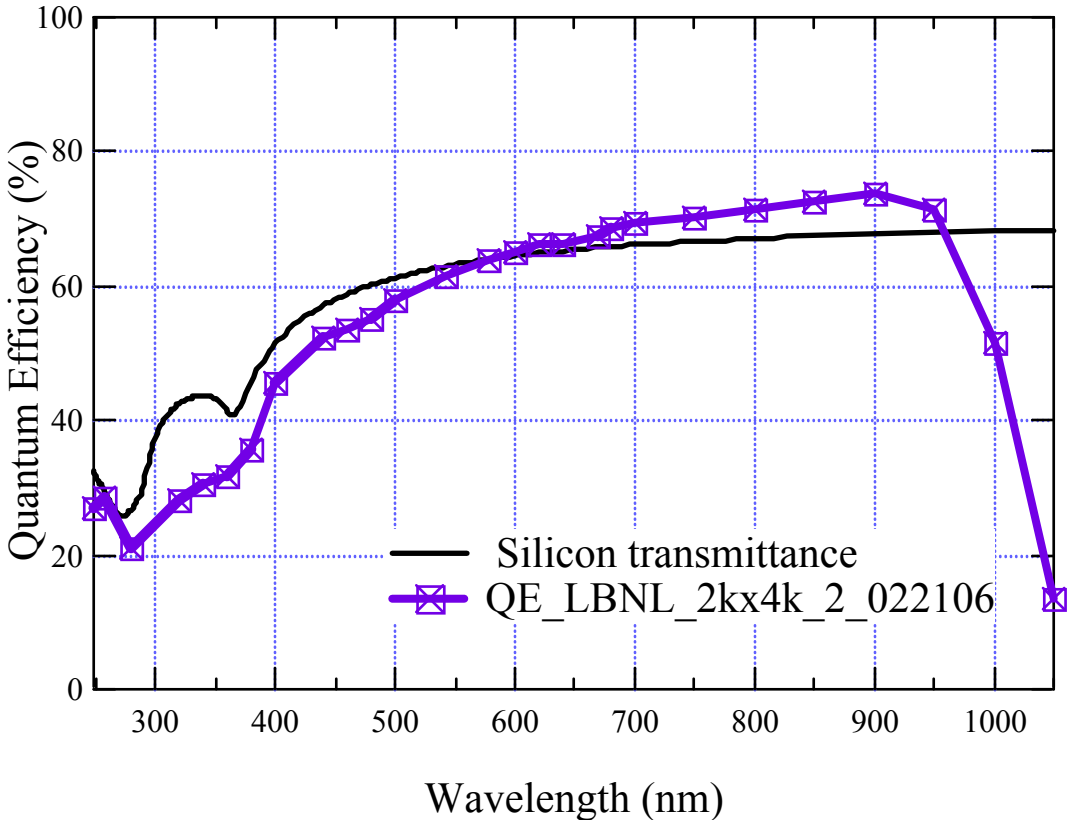








MBE Growth on 2k x 4k P-channel HP CCDs (No AR coating)

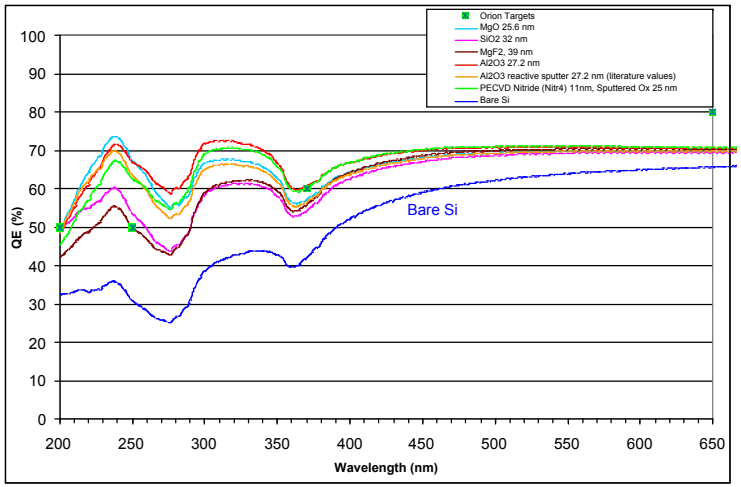


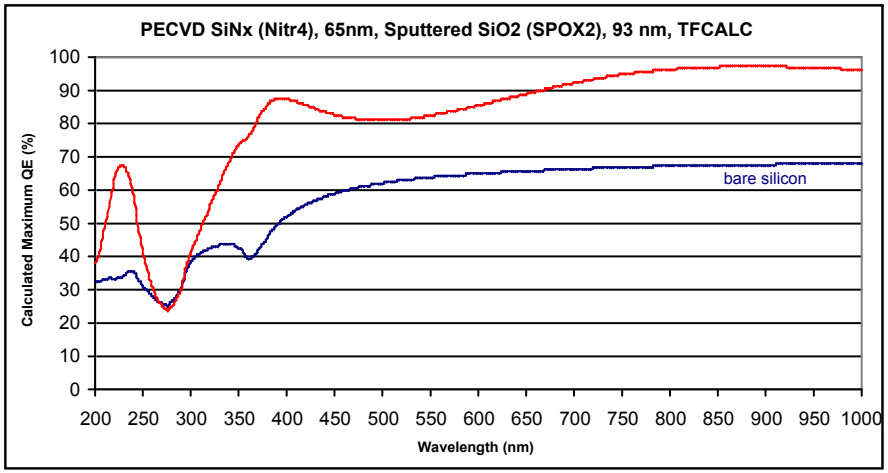
MBE modification using the thinnest delta layers were applied to 2k x 4k p-channel high purity CCDs. High resolution, low dark, and near 100% internal QE was demonstrated.

Maximizing QE with Antireflection Coatings

Antireflection (AR) Coatings Modeling

Wavelength	Silicon	SiO_2	Si_3N_4	Al_2O_3	MgO	MgF_2	HfO_2
200	0.97	1.55	2.50	1.83	1.90	1.42	2.50
250	1.56	1.50	2.20	1.83	1.80	1.40	2.30
300	4.77	1.47	2.15	1.80	1.78	1.40	2.12
350	5.53	1.47	2.10	1.80	1.75	1.40	2.10
400	5.43	1.47	2.07	1.79	1.74	1.39	2.02
600	3.89	1.46	2.02	1.77	1.73	1.38	1.98
800	3.66	1.45	2.00	1.76	1.72	1.38	1.96



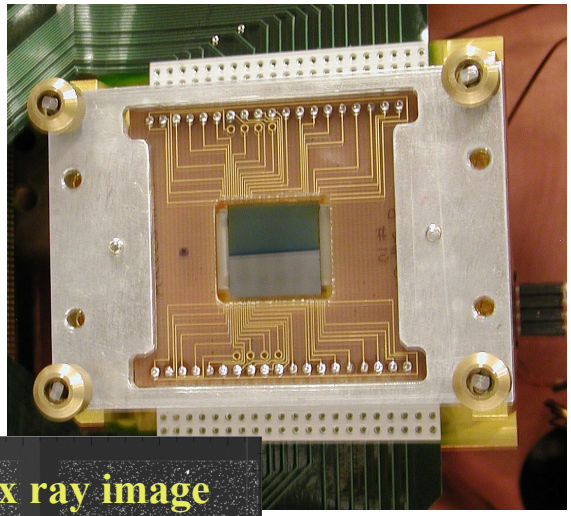


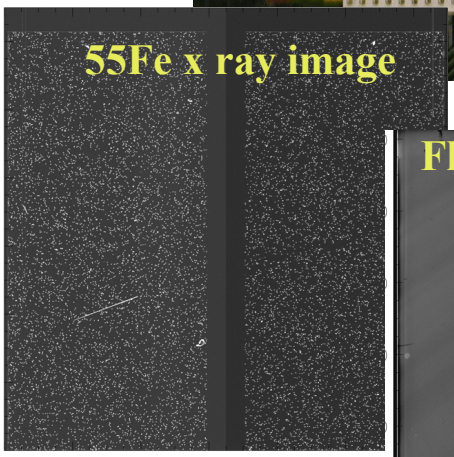
AR coatings for silicon were modeled for UV and broadband response

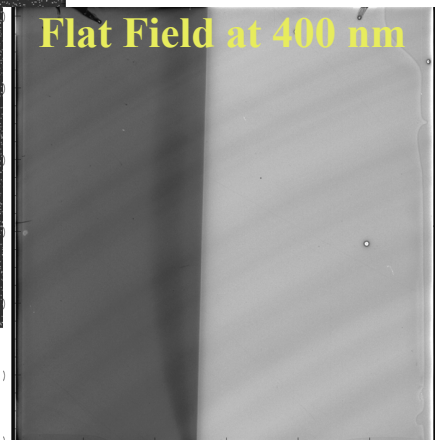
Single and multilayer designs were investigated

New deposition systems at JPL l expand options for multilayer coating design

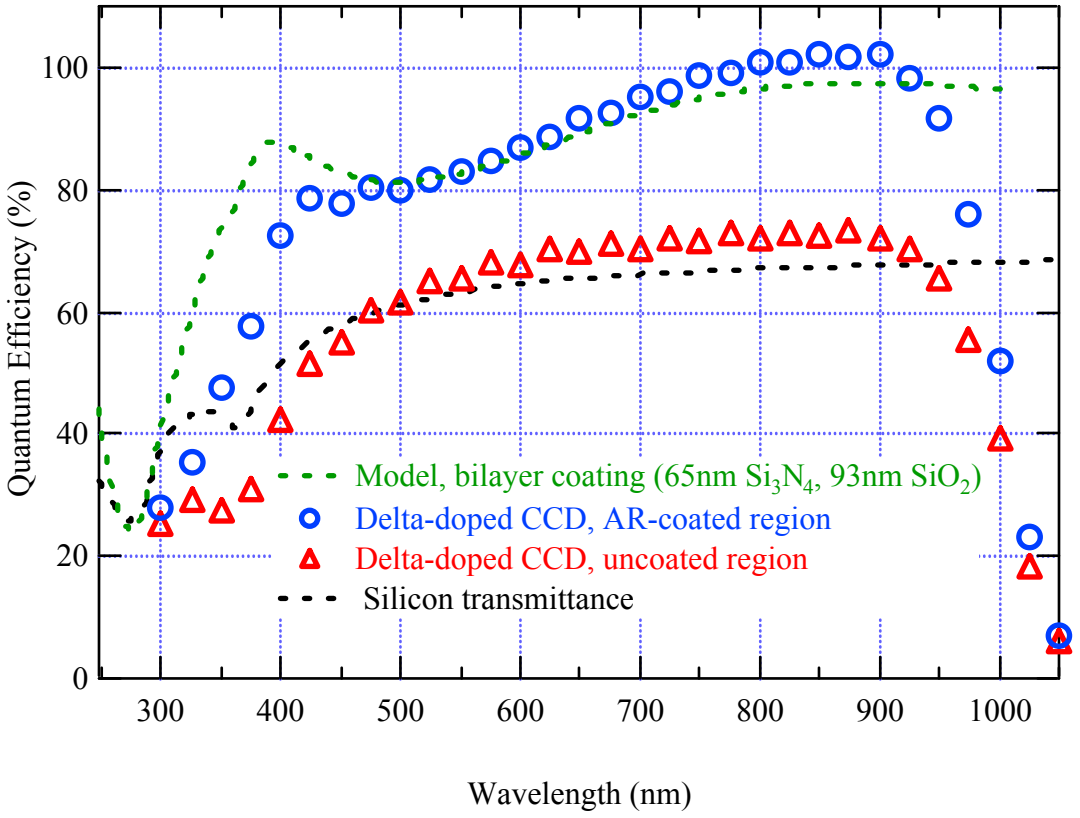
Antireflection Coatings





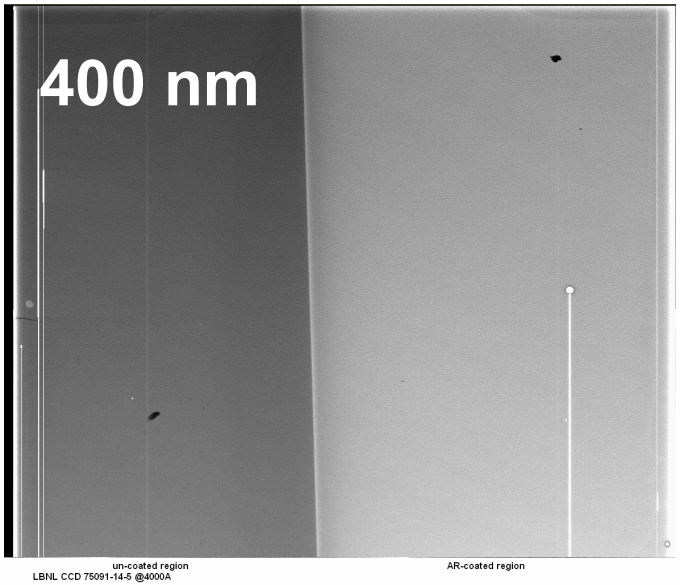


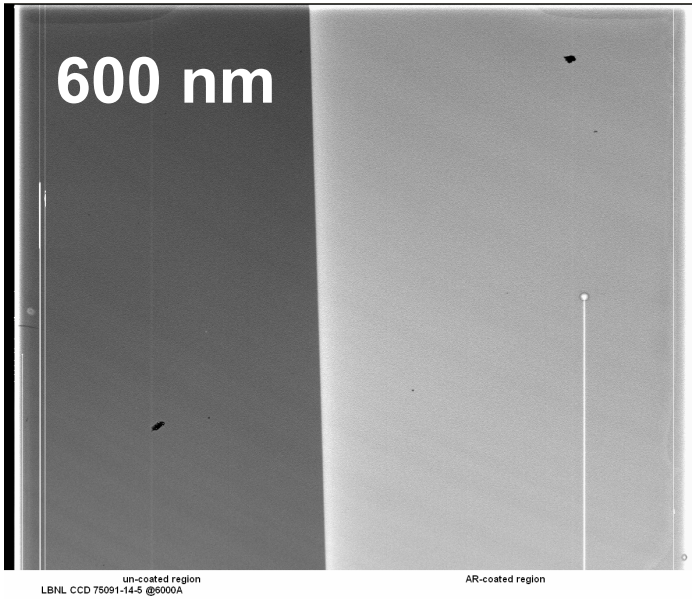
Deposition of Broadband AR coating
on Delta Doped P-channel CCDs

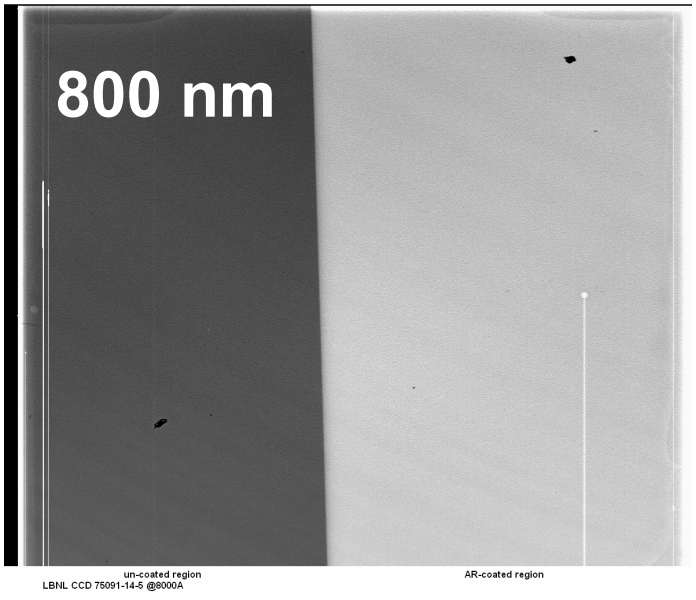


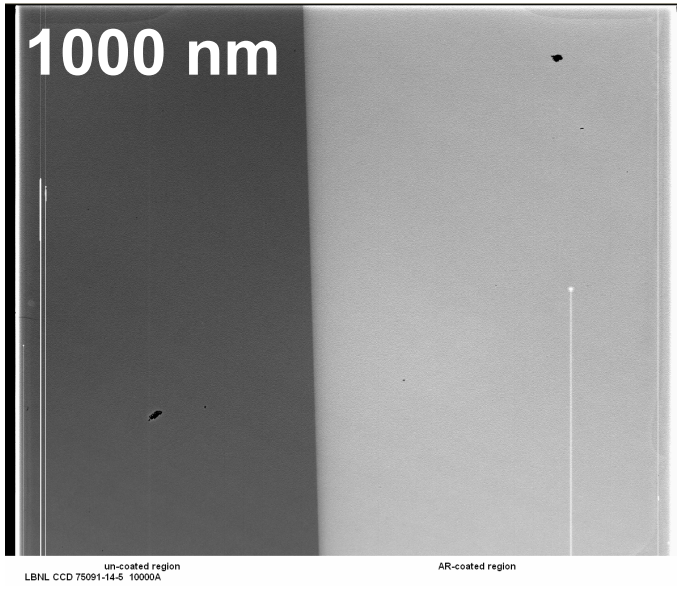
Broadband two layer coating (SiNx/SiOx) was deposited on 1/2 a 1k x1k DDCCD by PECVD
Excellent QE enhancement was observed. Flat Field at 400 nm shows grind marks from CMP.
X ray data showed that both amplifiers function properly.

Flat fields at various wavelengths









Summary

Delta doping process was developed on p-channel CCDs for MIDEX-Orion and JDEM/SNAP and was applied to large format (2k x4k) CCDs

Delta doping is applied to fully-fabricated CCDs (complete with Al metallization)

High QE and low dark current is demonstrated with delta doped p-channel CCDs

In-house AR coating is demonstrated